Simulation of the CERN-SPS Crystal Extraction Experiment

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Abstract

Simulation of the CERN crystal-extraction experiments at the SPS [1], including the real crystal geometry and SPS parameters, as well as multiple turns and passes, has been performed. Two crystals with different geometry have been tried. We argue that in both cases the extraction experiment suffered from the crystal edge imperfection. For the experimental conditions reproduced, the efficiency of the first ("twisted") crystal was found to be 12–18% (peak) in the angular range of 140–260 μrad (FWHM), depending on the vertical beam position at the crystal location. For the second ("U–shaped") crystal the peak efficiency was much the same, $\sim$19 %, while the angular scan FWHM reduced to 70 μrad. These results, as well as the beam profiles, are in agreement with measurements. Finally we suggest some ways to advance this experiment.

1 Introduction

The series of crystal extraction experiments is being performed at CERN[1], studying the feasibility of extracting protons from the halo of the beam circulating in SPS by a bent silicon crystal. These studies aim to model the beam parameters expected at the future Large Hadron Collider, and have in view possible application of the technique for a beam extraction from a multi-TeV machine. Such an extrapolation requires full understanding of the crystal extraction process. The present paper investigates these experiments by means of a computer simulation. Our aim is not only to compare theory vs measurement, but also to discover the factors apparently disturbing the crystal extraction process in [1].

The physics of channeling in a bent crystal is well established [2, 3]. Beam bending by a crystal is due to the trapping of some particles in the potential well formed by the field of atomic planes, where the particles then follow the direction of (are *channeling* in) the atomic planes. The channeling effect survives in a bent crystal until the ratio of the beam momentum p to the bending radius R becomes as high as the maximal field gradient ($\sim$6 GeV/cm in silicon). The crystal bend reduces the phase space available for channeling, thus decreasing the fraction of particles channeled. The scattering processes may cause the trapped particle to come to a free state (dechanneling).

In the present simulation we tracked protons through the curved crystal lattice with small, $\sim$1 μm, steps applying the Monte Carlo code CATCH [4]. This code uses the Lindhard's continuous-potential approach to the field of atomic planes, and takes the processes of both single and multiple scattering on electrons and nuclei into account. We assumed the crystal to have a perfect lattice.

The simulation of extraction was performed with parameters matching those of the SPS experiment: $\alpha_H = 2.07$, $\beta_H = 90\,\mathrm{m}$, $Q_H = 0.635$, $\alpha_V = -0.734$, $\beta_V = 24.4\,\mathrm{m}$, $Q_V = 0.583$. The vertical normalized emittance ϵ_V was normally $10\,\pi$ mm·mrad. Protons were tracked both in the crystal and in the accelerator for many subsequent passes and turns before eventual loss either at the aperture or in interaction with crystal nuclei. Tracking in the SPS used linear, 4 by 4 transfer matrices. The crystal was located horizontally at 10 mm from the beam axis.

The beam was excited by horizontal white noise at the opposite side of the machine, with kicks of

0.003 μrad r.m.s. value per turn. The expected impact parameters b and angles b' were studied earlier [5]. The b' value there was found to be $\ll \psi_p$. The b value should be $\sim$0.7 μm, i.e. quite close to the surface.

The crystal surface quality setting was rather conservative: miscut angle 200 μrad, surface non-flatness 1 μm, plus 1 μm thick amorphous layer superposed. This defines some 'septum width' of a few μm value. The protons tracking near the surface have taken all these details (as well as the *bent surface*) into account. We consider here two options. The *first*, with impact parameter below 1 μm and surface setting as described above, excludes the possibility of channelling in the first pass through the crystal. This is compared to the *second* option, when the crystal surface is assumed perfect, i.e. with zero septum width.

2 "Twisted" crystal

The first extraction experiments [1] were performed with a "Serpukhov-type" bending device, and have given results more sophisticated than expected: the extraction efficiency was rather small, around 10%; extraction occurred in the angular range of 200 μrad FWHM, much wider than the beam divergence or critical channelling angle (14 μrad); two peaks appeared both in the horizontal and vertical profile of the extracted beam at the crystal orientation far away from the best one; the angular range of extraction depended on the vertical beam position.

In the laser measurements it was found that the bent crystal is deformed vertically, called 'twist' in the following. As a result, the planar direction at the entrance to the crystal was a function of the vertical position. The measured crystal properties were used as input to the simulations. The total bending found for this (3 cm long, 1.5 mm thick) crystal was 8.5 mrad. In the experiment, different vertical beam positions (bump) and different vertical emittances ϵ_V have been tried in order to investigate the twist effect. Our simulation followed the program of the SPS experiment. Table 1 summarizes the extraction efficiencies, the widths of the angular scan and of the extracted-beam profiles (observed 20 m downstream) obtained in the simulation for $\epsilon_V = 10\pi$ and 1.5π mm·mrad. The extraction efficiency as a function of tilt angle is shown in Fig. 1 both for nominal position (•) and bump of 2 mm (o). The increase of ϵ_V to 20 π mm·mrad has slightly reduced the efficiencies. This is summarized in Table 2, where the peak efficiency is plotted as a function of ϵ_V and the vertical position of the beam at crystal.

Table 1: Summary of simulation for ϵ_V=10π and 1.5π.

	SIMULATION	
FWHM	Bad surface	Good surface
nominal		
X (mm)	1.9	1.7
Y (mm)	3.4	1.7
scan (μrad)	140	30
efficiency(%)	18	40
bump 1 mm		
X (mm)	3.5	1.1
Y (mm)	3.1	1.8
scan (μrad)	170	90
efficiency(%)	16	24
bump 2 mm		
X (mm)	2.2	1.0
Y (mm)	2.2	2.0
scan (μrad)	260	200
efficiency(%)	12	15
ϵ_V=1.5		
X (mm)	1.6	0.8
Y (mm)	1.7	0.7
scan (μrad)	110	25
efficiency(%)	19	52

In the SPS experiment, the nominal vertical position was $\sim$1 mm away from the 'twist middle'. The ϵ_V typical value was $\sim$10 π mm·mrad. Therefore the number of 16% for the peak efficiency (and 170 μrad for the angular scan FWHM) seems the most relevant one to compare with the experimental results, namely 10±1.7% and 200 μrad. The systematic error caused by some uncertainties in the vertical position, ϵ_V value, and twist detail, can be estimated from Table 2 as a few per cent for the peak efficiency. We may conclude that the perfect-surface simulation has often pre-

Table 2: The peak efficiency (%) plotted vs ϵ_V and the vertical beam position (bump).

Bump [mm] ⇓	ϵ_V [π·mm·mrad] 1.5	10	20
0	19	18	16
1		16	15
2		12	

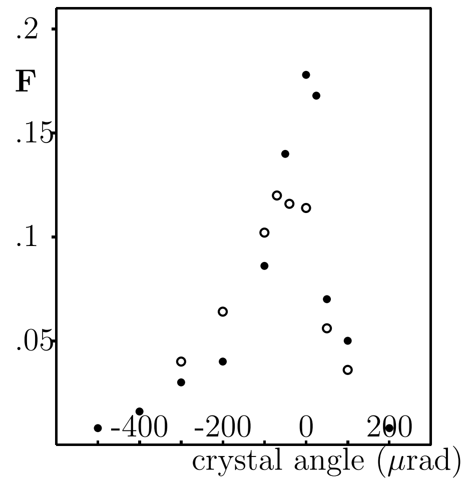

Figure 1: Angular scans of efficiency for twisted crystal. Nominal position (•) and bump of 2 mm (o)

dicted narrow high peaks, which have not been observed. The imperfect-surface option roughly followed the experimental observation. Both the angular scan FWHM and the efficiency value depend on the bump in the same way as it was observed at the SPS. The extracted beam vertical width tends to decrease with vertical displacement, while the horizontal width has no trend but sizeable fluctuations. Both features seem to agree with experimental observation. There is quantitative agreement with the measurement, but the price for this agreement is the assumption of crystal edge imperfection. The twist effect was minor for the *peak* efficiency, and cannot alone explain the large angular width of the extraction.

3 "U-shaped" crystal

After the above analysis, a prediction was made in [6] for the new, "U-shaped" crystal[7] which has no twist. This crystal is 4 cm long with 8.2 mrad bending. Fig. 2 shows the angular scan simulated for this crystal with edge imperfection, which is in good agreement with the first experimental results[7]. As compared to the "twisted" crystal, there was expected no sizeable change of efficiency, in accord with the first observation. Such an agreement indicates that the new crystal also has some edge imperfection. For an ideal crystal and a very parallel incident beam the simulation gives the peak efficiency ∼50% and the narrow angular scan (25 μrad FWHM).

4 Experiment Advancement

An essential advancement of the crystal extraction experiment would be the measurement of the first-pass contribution to efficiency. This is quite important for understanding both of the crystal-edge work (measuring "septum width") and of the crystal co-work with the other elements of accelerator (multiple passes/turns). One can distinguish the first pass from the secondary ones owing to their difference in time (first comes first) and space (secondary pass comes deeper in the crystal). The time-synchronyzing ("kick mode") has difficulty caused by unavoidable mixing of the "first-pass" protons from later turns. For a spatial separation one way is a thin amorphous layer superposed on the crystal surface to suppress the first pass (W.Herr). Here are some other ways:

Microscope. Applying a skew cut on the exit face of a crystal, one can make the bending angle to depend on the impact parameter b (a principle of any microscope). The bent beam profile downstream the crystal would be then an amplified profile of this beam at the crystal face.

Energy loss [8]. The $\delta E/\delta z$ *deposited* in the crystal may indicate whether the proton is extracted with the first pass or with the secondary one, due to the escape of δ-electrons near the sur-

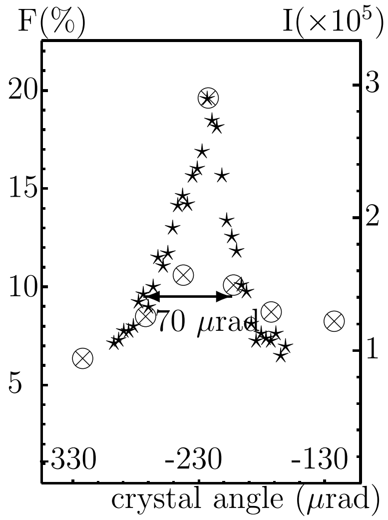

Figure 2: Prediction (⊗, left scale) and measurement ($\star$, right scale) for the U-shaped crystal.

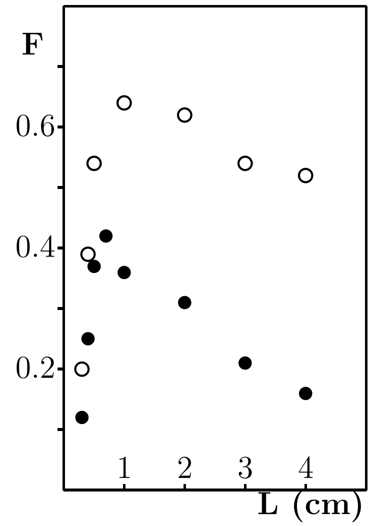

Figure 3: Extraction efficiency vs crystal length. For edge imperfection (•) and ideal crystal (o).

face (depending on b). And vice versa, selecting 'first-pass' in some other way one may observe an interesting $\delta E/\delta z$ spectrum (fwhm≈0).

Masking [6]. One can scrape the circulating beam by a collimator during the crystal extraction, thus suppressing the secondary passes.

Tune resonance [6]. It was shown that for an *imperfect* edge of a crystal the extraction efficiency drops near the tune resonance (for the same given parameters of incident particles). The resonance both dip and width depend on (are roughly proportional to) the septum width.

Crystal rotation in "FNAL geometry" [9]. In the different geometry of extraction [10] there is an extra degree of freedom. The crystal rotation *normal* to bending plane results in a controlled change (with steps of ∼0.02 μm) of septum width.

Fig. 3 shows the extraction efficiency as function of L, simulated for an untwisted crystal with constant curvature. A short (∼1 cm here) length could be a "cure" to any imperfection of a crystal, as the protons make more passes.

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